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CENTRAL INSTITUTE FOR INDUSTRIAL RESEARCH

Oslo - Blindern, Norway

Agreement No. N-15-MWP-N-62

DEVELOPMENT OF EXPLOSIVE TECHNIQUES IN METAL FORMING.

Status Report No. 1

July 1, 1962 through December 31, 1962

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CENTRAL INSTITUTE FOR
INDUSTRIAL RESEARCH

Oslo - Blindern, Norway

January 31, 1962

Børge Høgland

B. Høgland
Principal Investigator

St. 3689/0/62 07 07

F O R E W O R D

The present research project represents part of more general research activities relating to fabrication and forming of metals currently being conducted at the Central Institute. Literature studies of explosive forming were initiated in 1960 and have later been supplemented by visits to a large number of industries and laboratories actively engaged in such work.

In the work under this contract we will cooperate with the Norwegian Defence Research Establishment. As of July 1, 1962 the U.S. Government through The Mutual Weapons Development Program is jointly sponsoring the prosject.

This report covers the work conducted from July 1 through December 31, 1962.

Oslo - Blindern, Norway
January 31, 1963

CENTRAL INSTITUTE FOR
INDUSTRIAL RESEARCH

Alf Sanengen
Director

ABSTRACT.

The building of experimental facilities has been finished and preliminary experiments conducted. Explosive charges up to 1 kg, can be detonated in the three meter wide tank.

A bibliography containing about 1500 references is organized and important technical reports have been purchased.

Detailed planning of experiments and necessary equipment has been the main activity in the reported period. The program comprise the following main subjects: Die construction, dynamic formability, structural changes, forming at elevated temperatures, welding and compaction of powder.

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1.0 INTRODUCTION.

The current interest in explosive forming is convincingly demonstrated by the very large number of technical papers and articles which have been published since 1957. In spite of this considerable effort, comparatively few, but never the less important, industrial applications have developed. One contributing factor to this delay is obviously a general scarcity of fundamental investigations to provide a backing for the technological feasibility studies. However, certain limitations of the processes currently in use have been disappointing, indicating that new innovations will be necessary if a more general break through for explosive forming is to take place. In agreement with American investigators engaged in this field, we believe that there is very good reason to regard the future with confidence and optimism.

The scope of the research program originally suggested in our proposal of January 17, 1961, has been revised on the basis of experiences gained in the meantime. The aspects relating to extrusion and extrusion casting have thus been omitted in favour of welding and compaction of powders. This is mainly due to the unexpected rapid development of commercial high energy rate machines which have put many industrial laboratories in a much more favourable experimental position than ours. Furthermore, the aspects of explosive welding and compaction seem to be considerably more promising than previously expected.

The activities in the period covered by this report have largely been concerned with the following items:

1. Construction and building of experimental facilities.
2. Organization of litterature information.
3. Detailed planning of experiments.

The report gives a brief description of the problems we intend to study and the experimental procedure. It is realized that capacity limitations may cause certain reductions of the program, but we expect that significant contributions can be accomplished in each of the main areas.

2.0 LITERATURE SURVEY

The survey covers literature on high energy forming from all parts of the world.

The ten bibliographies and other literature information sources listed below are intergrated in one bibliography containing approximately 1500 references. The system of organizing is in accordanse with the one adopted in reference (1).

(1) "High Energy Rate Metal Working Bibliography"
Prepared by Daniel E. Strohcker
North American Aviation Inc.
Columbus, Ohio
January 1, 1962
Prepared under MEP 8006

(2) "Bibliography on High Speed Deformation of Materials"
Prepared by J.R. Cotner and J. Weertman
Materials Science Department
Northwestern University
Evanston, Illinois
May 15, 1961
ASTIA AD 261 376

(3) "High Energy Rate Forming Bibliography"
American Society of Tool and Manufacturing Engineers
Detroit, Michigan
ASTME Paper No. SP60 - 187

(4) "Bibliography on Explosive Metal Working"
Prepared by C.T. Olofson and F.W. Boulger
Defence Metals Information Center
Battelle Memorial Institute, Columbus, Ohio
April 7, 1960
DMIC Memorandum 51

(5) "Explosive Metal Forming and Electro-Hydraulic Effect Survey of Soviet Literature"
AID Report 60 - 106
December 14, 1960
ASTIA AD - 250 074

(6) "OTS Selctive Bibliography on Explosive Metal Forming"
Office of Technical Services
U.S. Department of Commerce
Washington 25, D.C.
December 1960
USCOMM - DC - 61404

(7) "OTS Selctive Bibliography on Explosive Metal Forming"
Office of Technical Services
U.S. Department of Commerce.
Washington 25, D.C.
December 1961
USCOMM - DC - 46294

(8) "High - Impact Metal Forming 1957 - 1960"
An Annotated Bibliography
Compiled by A.A. Beltran
Lockheed Aircraft Corporation
Sunnyvale California
July 1960
ASTIA AD - 241 995

(9) "Explosive Forming"
An ASTIA Report Bibliography
Compiled by Katye M. Gibbs
Hq. Armed Services Technical Information Agency
Arlington Hall Station
Arlington 12, Va.
Februaray 1962
ASTIA AD - 270 900

(10) "Hochleistungsumformung" (High Fnergy Forming)
Part 2 - Bibliography
Prepared by Gerhard Gentzsch
Verein Deutscher Ingenieure
Düsseldorf, Germany
August 1962
DK 621.970 - 186.7

(11) "The Electronic Information Searching Service for abstract references from literature published in the year 1961 regarding Explosive Forming"
By the Documentation Service
of the American Society for Metals
Metals Park, Ohio

(12) The running scanning of the most important technical journals by the explosive forming group members.

The first bibliography is the final report prepared under US Army research Project ORD - 241. This bibliography provides abstracts of approximately 420 articles on, and related to high energy rate metal working. The references have been organized into groups according to the main topic of the reference. The major subjects covered in this bibliography are:

1. Safety
2. Energy Sources
3. Energy Transfer Mediums
4. Facilities and Equipment
5. High Energy Rate Forming
6. High Energy Rate Machining
7. Theory of High Energy Rate Phenomenon
8. High Energy Rate Welding
9. Work Hardening by High Energy Rate Methods
10. High Energy Rate Powder Compaction

The bibliography is crossed-indexed by matter and author. An author index is included.

The second bibliography, US Air Force contract No 29(601) - 4343, presents 293 abstracts of the literature from 1950 to 1961, dealing with high speed deformation of materials. References concerning stress wave propagation are included. The arrangement of the abstracts is chronological with an alphabetic sequence within each year. An Author index is included.

The third bibliography is presented as a technical paper in Advanced High Energy Rate Forming, a compilation of technical papers presented at ASTME seminars in 1961. This bibliography provides 394 references which are not abstracted. The arrangement is alphabetic by author or by title when no author is named.

The fourth bibliography, prepared by Battelle Memorial Institute, provides 210 references of a general nature on explosive forming. The references are not abstracted and no attempt of arrangement according to subject matter has been made. The arrangement is alphabetical by author or title when no author is named.

The fifth bibliography, prepared by US Air Information Division, contains 13 references with abstracts of Russian literature dealing with various aspects of high energy forming techniques. The arrangement is alphabetical by author.

The sixth bibliography, prepared by US Department of Commerce, presents 32 not abstracted references of reports concerning explosive forming and related subjects. The bibliography includes reports listed in the two OTS monthly abstract journals: "US Government Research Reports" and "Technical Translations", through 1960. The arrangement is alphabetical according to company.

The seventh bibliography, prepared by US Department of Commerce, presents 66 not abstracted references of reports on high energy rate forging, high impact forming, use of explosive energy in metal-working operations, and use of the Dynapak machine. The bibliography includes reports listed in the two OTS monthly abstract journals: "US Government Research Reports" and "Technical Translations", through 1961. The arrangement is alphabetical by source.

The eighth bibliography was prepared by Lockheed Aircraft Corporation in conjunction with an US Air Force contract on explosive forming. This bibliography is primarily concerned with articles on forming with high explosives. However, articles on electro-discharge forming, high speed machining, impact extruding and shooting of bolts into metals have been included. It contains 130 abstracted references of technical reports and open literature. The arrangement appears alphabetically by author or title.

The ninth bibliography, prepared by US Armed Services Technical Information Agency, provides totally 340 references:

14 abstracted references covering the period from 1942 through 1952 have been selected from the ATI collection.

86 references, all but a few abstracted, covering the period from 1952 through 1961 have been selected from AD report collections.

Within each of these categories, military reports are arranged alphabetically by source and title, reports prepared by Department of Defence contractors, are listed alphabetically by source, contract, and then by title.

205 references from open literature, 27 from patents, and 8 from commercial papers are not abstracted.

These citations appear alphabetically by author or title within each category.

The tenth bibliography, presented by the Society of German Engineers, provides 320 references from American and European literature of which approximately 80 % are abstracted. The references listed in this bibliography have been organized into groups according to their main subjects which are:

1. High Energy Rate Forming - general references
2. Explosive Forming
3. Electric Discharge Forming
4. Electromagnetic Forming
5. Pneumatisk-Mechanical Forming
6. Special Processes

The arrangement of the references is alphabetical by author or title within each group. Included are:

1. Chronological index of reference codes
2. Index of technical journals referred
3. Author index
4. Subject index

The bibliographic electronic machine search, by the documentation service of the American Society for Metals, presents 112 abstract references concerning Explosiv Forming and similar and related items compiled from literature issued in the course of 1961.

The members of the team participating in the current research project, are continously scanning American and European literature for the purpose of keeping the bibliography up to date.

A representative collection of the more important articles referred to in the bibliography, has been organized in a file. This provides an easy access to the technical information required for satisfactory progress of the research activities.

3.0 EXPERIMETAL FACILITIES

The explosive forming facilities are located at Dompa proving ground of the Norwegian Defence Research Establishment. The general lay out is shown in Fig. 1. The facilities comprise the following units:

1. A detonation pit with hoist arrangement.
2. A preparation shelter.
3. An instrument laboratory.

The choice of construction principles has largely been determined by the local conditions at Dompa such as; winter temperatures below minus 20 °C, proximity of instrument laboratories and sewer pipes which would not tolerate appreciable shocks through the ground, a soil quality of low strength (mainly clay) and high humidity etc. A brief description of the three units is given in the following. The tank construction is of the same general type as used by Lockheed Aircraft Corp. (1) and Battelle Memorial Inst. (2).

3.1 Detonation pit.

Fig. 2 gives a vertical section through the bottom part of the detonation pit. It consists of an outer circular steel sheet piling, 4 meters deep, resting om solid rock. The upper edge rise about 1 meter above ground level. An anvil shaped concrete sole, 1/2 meters deep, cast in contact with solid rock constitutes the bottom of the pit. Radial motion of the steel piling is prevented by the concrete and the surrounding soil at the bottom and by a steel ring at the ground level.

The inner cylinder of the pit (the tank), which is 3.35 m high and 3 meters wide, is constructed from 12 mm mild steel plates, cold formed and joined with one circular and two longitudinal welds. Radiographic inspection of the welds proved a quality corresponding to class 4 in

the I.I.W. system. The tank is insulated on the outside surface with foam polystrene, only leaving a free zone of about 2 feet at the bottom. 3 cm

The tank rests on a steel flange to which an auxiliary steel ring (12 mm) is welded in order to provide an 13 cm deep annulus for sealing purposes. The lower part of the annulus is filled with rock wool on top of which "Icorub" (a proprietory, non-curing, bituminous rubber compound) serves as a water tight seal.

The top of the concrete anvil is covered with a layer of linoleum, which provides a smooth surface for a densly coiled 5 cm fire hose. In operation, the hose is inflated with air of about two atmospheres and serves as a shock absorber for a 12 mm thick steel plate resting on it. A second layer of linoleum separates the plate and the hose. A cylindrical section is welded to the circumference of the plate in order to guide the downward motion when a shot is fired. It is estimated that this bottom construction can take up at least 5.000 kgm of energy without damage to plate or fire hose.

Air supply to the fire hose and the surrounding space under the steel plate is taken through a duct in the concrete sole. The construction details indicated in Fig. 2 need no further comments.

In the space between the bottom assembly and the tank wall a 15 cm perforated. copper tube, serving as an aerator manifold, is positioned. The tube is shaded from direct impingement of shock waves. Two rows of 0.7 mm diameter holes are drilled along the entire circumference of the tube. The rows are oriented downwards and with a spacing which gives the same air flow on both sides of the tube. About 200 holes are uniformly distributed in each row. Compressed air is fed to the copper tube through a 5 cm rubber hose alongside the inner tank wall. In operation this manifold has been found to give a uniform, protective curtain of air bubbles close to the tank wall.

To prevent freezing during winter time, two heating elements of 1000 W each, are submerged in the water. This has been sufficient to maintain the temperature above about 10 °C even in very cold weather.

The space between tank and steel piling is kept free of water by means of a small centrifugal pump.

The crane girder with a lifting capacity of 7 tons, is crossing over a close by road. This permits lifting of heavy dies directly from a truck and into the tank. At the present only a manually operated hoist of 1 ton capasity is mounted on the girder.

3.2 The preparation shelter.

A simple, wooden shelter, 3 by 4 m, is built close to the detonation pit. The door is 2.50 m broad, allowing big forms to be prepared in the shelter. The various valves and pressure gauges for controlling the use of compressed air, are assembled in the shelter. An inspection window gives the operator direct view to the detonation pit. Compressor and storage tank are placed just outside the shelter. Details of the compressed air supply system are given in Fig. 3.

3.3 Laboratory for measuring equipment.

A small laboratory of two rooms, 3 by 4 m is arranged in connection with the existing balistic laboratory at a distance of some 25 m from the preparation shelter. This laboratory provides facilities for instrumentation set up in acceptable vicinity of the detonation pit. The facilities are in accordance with well established laboratory practice and will most probably meet the requirements of our measuring program. No special feature deserves further description at the moment.

4.0 EXPLOSIVE FORMING AT AMBIENT AND SUBZERO TEMPERATURES

4.1 General.

The current interest in explosive forming is in part due to the simplicity of operation and low cost of equipment characteristic for forming at ambient temperatures with water as transfer medium. The accomplishments of the process have been encouraging, but price considerations and lack of technical know how have thus far limited its field of application. Further development of the technolcgy and a better understanding of the basic mechanisms, is obviously required in order to extend the capabilities of the process.

The research program outlined in the following will mainly be concerned with problems relating to forming at room temperature, but an attempt will also be made to form austenitic stainless steels at much lower temperatures. The latter forming conditions are of interest in conjunction with a study of the structural changes caused by shock waves and high strain rates at different temperatures. Furthermore, a recent report (3), claims that unusual strengthening can be accomplished under such working conditions.

4.2 Product Development.

A few sheet metal parts have been tentatively selected for a technological feasibility study in cooperation with industry. The parts are characterized as difficult to fabricate with the facilities available in the shops. Since no final decision has been made regarding the extent of this work, a detailed description will be postponed until a later report. Only the type of products considered are given below.

1. Parts in the combustion chamber of a gas turbine engine and exhaust annulus.
2. Replacement parts for the intake duct of jet airplanes and similar items.
3. Bottoms for pressure vessels.

4.3 Development of inexpensive forming dies.

The importance of tool costs increase rapidly as the number of parts to be produced goes down. This applies especially when the parts are very large or have a complex geometry. In these cases, dies are often made of concrete with a lining of reinforced epoxy, or cast from a low-melting alloy. (Kirksite). Depending upon the strength properties and gauge of the material to be formed, such dies may last for production runs of 1 to 100 pieces (4). Thus an important, but limited field of application is indicated. If even less expensive dies could be fabricated, new fields of application would be opened for explcsive forming techniques. In an attempt to contribute to this end, an exploratory study of potential advantages of using a preshaped, reinforced epoxy shell with a backing of unbonded sand is undertaken.

The shells will be shaped and cured in contact with a model (wood or plaster of paris) and subsequently clamped to the draw ring by means of a flange. This assembly is then mounted on a corresponding flange welded to a perforated, sylindrical steel container. A rubber (or plastic) bag filled with sand occupies the entire space withing the container. Together with the epoxy shell, the bag constitutes a vacuum tight system allowing direct contact between the sand and the shell.

The sand is now vibrated with the die cavity in a downward possition in order to eliminate air pockets at the shell surface and the system is finally evacuated. The atmospheric pressure on the external surface of the bag has been shown to give a very substantial hardening and stiffening of the sand with little change of volume. To obtain the full advantage of this hardening effect, the sand will be internally fortified. At this stage the die can be handeled like any other die.

When the die cavity is evacuated prior to forming, the pressure on the epoxy shell is relieved, permitting it to return to its original shape. Until the reology of the fortified sand system is better known, it would be difficult to predict its response to this change. It is expected, however, that no significant back pressure will be built up. The question of how the die behaves under impact conditions can only

be answered through actual experiments. For this purpose a die of about 30 cm diameter will be constructed.

If satisfactory results are accomplished, this method of die fabrication will be tried in connection with the product development program referred to in the preceeding section.

4.4 Dynamics of deformation and blank displacement during die forming.

Earlier publications relating to explosive forming of sheet metals (5) present experimental evidence of improved ductility under conditions of impulsive loading. These results seem to be in conflict with more recent observations (6) indicating a quite general reduction of the same property. In some cases diverging conclusions are obviously due to the use of different test materials and/or basis of comparison. In other cases it can be suspected that differences in testing conditions may have influenced the results significantly. These complications, together with a general scarcity of quantitative measurements of dynamic parameters, do not encourage conclusive statements at the present time.

Investigations of strain rate effects in uniaxial tension have demonstrated that localized plastic instability occurs near the impact end at a given impact velocity characteristic for each material (7). Wood et al. (8) have calculated such critical velocities for a number of metals and alloys, obtaining values rangeing from about 30 to 507 ft/sek. At impact velocities below these limits a plastic wave is propagated along the tensile specimen. Due to the non-uniform strain distribution, the average strain rate depends on the gage length and may differ significantly from the local strain rate in the plastic wave.

Davis et al. (9) have recently studied the tensile behavious of freely expanding rings after impulsive loading in a radial direction. Since all parts of the ring are stretched simultaneously, no plastic wave propagation occurs. Average strain rates of the order of 10^3 to 10^4 sek^{-1} have been accomplished without spontaneous plastic instability.

These two strain mechanisms are also important in deep drawing, although a biaxial stress system is operative in this case. The impact component is caused by the circumferential clamping by the pressure ring and in later stages, by the bending over the draw ring. It is not known to what extend this affects the drawability through pre-mature fracturing caused by local plastic instability. Pipher et al. (10) have reported typical blank velocities and average strain rates between 278 and 796 ft/sek. and 46 to 407 sek^{-1} respectively. This indicates that critical impact conditions may occur when the boundary conditions are unfavourable. On the other hand the strain rate is quite modest if a uniform straining as in the expanding ring is prevailing.

When these problems have been studied in earlier experiments, either free forming or deep hemispherical dies have been used. This implies that only the finished cup is available for inspection giving little information about the transient states during forming. Furthermore, the speed of forming is poorly defined since dicipation of kinetic energy gives a gradual decrease of blank velocity.

In the current investigation a different approach will be attempted. The motion of the blank will be arrested in shallow dies at four pre-determined deformation stages. In each operation the start and termination of blank motion will be recorded at varying distances from the centerline of the die, as indicated in Fig. 4. Adjustments of die profile can then be made on the basis of time records, thus establishing an improved "quenching" of motion in subsequent experiments. After each forming, detailed studies of local elongation, thinning and hardness will be carried out.

Through controled variations of blank material, explosive charge, clamping pressure on the flange and draw ring radius this experimental technique is expected to provide quantitative information about the local, instantanicus strain distribution due to impact loading. The instantanious shape of the blank during forming is an additional aspect of considerable interest.

The experiments indicated above will also provide information about the instantanious blank velocity at various distances from the center line. If these data are sufficiently accurate and reproducable, calculation of kinetic energy as a function of blank displacement will be possible. Related to the corresponding strain distribution this may permit deductions relating to basic aspects of dynamic plastisity under conditions of biaxial stress. These aspects are of considerable technological interest since, control of material flow appears to be essential in die forming.

A study of the correlation between spring back and magnitude of impact with the die is also facilitated by the velocity data becoming available.

The die shown in Fig. 4 has already been build and tested in a few preliminary experiments. The planar contacts will be of the "postage-stamp" type and the signals will be fed to a Tectronix oscilloscope through a identifying network. The materials tentatively selected for investigation are mild steel and two or more of the stainless steels given in Table I.

4.5 Structural changes in austenitic stainless steels due to impact and high strain rates.

From a formability point of view both austenitic and semi-austenitic stainless steels performed very well in explosive forming operations. However, Verbraak (11) and others have shown that fatigue life and stress corrosion properties are impaired under certain working conditions. This is mainly attributed to the severe mechanical twinning observed in favourably oriented grains. The effect of other structural changes such as martensite precipitation and micrp-cracking may also be expected to contribute, although experimental evidence thus far is less convincing.

Verbraak further observed that the corrosion resistance could be improved through a reduction of the pressure amplitude in the shock wave. The interpretation of this observation is not entirely clear

since simultaneous plastic deformation and impact with a die was allowed to take place. To clarify this point, experiments will be conducted in which a study of the separate effects of shock wave, rate of deformation and impact with a die will be attempted.

The testing materials for the investigation will be produced by means of the forming die shown in Fig. 4, using the following steels given in Table I: SAE 301, 304, and 316. Three sets of experiments will be conducted:

1. The blank is supported on polyurethane foam in the die cavity.
2. A steel anvil is placed in the die cavity with a spacing of about 1 cm to the blank.
3. Die forming with varying degrees of deformations.

The first experiment is hoped to give a pure shock wave effect without significant interference from plastic deformation or retardation impact. The second experiment will give the impact effect at maximum velocity superimposed on the shock wave effect. A large blank diameter is chosen in order to minimize plastic deformation. Finally, the general case incorporating shock, impact and plastic deformation is given. Suitable explosive charge and stand off parameters will be determined in auxiliary experiments.

The effect on structure and material properties will be studied as follows:

1. Corrosion testing in a salt spray environment.
2. Fatigue life measured in an Amsler high-frequency pulsator.
3. Metallographic investigations.
4. X-ray diffraction studies using a Simens texture gonoimeter with a proportional counter with pulse height discrimination.

Explosive forming of austenitic stainless steels at sub-zero temperatures may have a much stronger influence on the structural changes than at R.T. since the austenite stability is progressively

reduced under these conditions. Evidence of this was recently reported in an article concerned with strengthening of the steels through deformation at very low temperatures followed by tempering (3). SAE steels No. 301, 347 and AM 355 will be imploid in an attempt to carry out explosive forming at about - 80 °C. The experimental conditions have not yet been decided, but a diaphragma technique similar to the one described for hot working will be considered.

If the forming is successfull, structural investigations and measurement of mechanical properties will be carried out as above.

5.0 EXPLOSIVE FORMING AT ELEVATED TEMPERATURES.

5.1 General.

Explosive forming at elevated temperatures is not a new idea. Several laboratories in the U.S.A. have successfully formed refractory metals using air, liquid metals, salt baths, heated sand, alumina and other powder material as transfer media. (12) Although encouraging results have been achieved in the case of W, Mo, and Ti-alloys, etc. these techniques have not been met with much enthusiasm in industry. Apparently this is mainly due to the complexity and/or limitations of the systems used, and/or general sceptisism when operation of high explosives at elevated temperatures is concerned.

The need for further development of the hot working techniques must also be seen in relation to the limitations which have recently been demonstrated in the case of explosive forming at ambient temperature. It appears that formability under the latter conditions often is less than in comparable conventional techniques. Also, the early claims that spring back and local thinning are drastically reduced, have been modified considerably. Further development of the cold working techniques may of cause improve this situation, but the need for a supplementary high-temperature process is clearly indicated.

An experimental set up for explosive forming at elevated temperatures and the potential technological and metallurgical advantages of the process are outlined in the following sections. It is characteristic for this technique that only the blank is heated and that rapid cooling or quenching is possible shortly after forming. This opens a wider scope for the process. It may f.inst. become possible to harden martensitic steels in the die. However, at the present stage the technological feasibility of the process still remains to be demonstrated.

5.2 High temperature die - experimental conditions.

The main features of the forming die are indicated in Fig. 5. The blank is clamped between two holding rings. The dimensions are

depending on the type of operation and the clamping force required. It is expected that various degrees of stretchforming and drawing can be realised through correct adjustment of the parameters.

The blank assembly is thermally insulated from the die and the transfer media by vacuum and/or suitable insulating materials. The only critical point of contact is at the drawing ring where strength and insulatinn requirements may conflict. However, the effect of heat losses at this point is minimized by the close proximity of the holding rings which serve as a heat reservoir. If necessary, additional heating of the rings can easily be accomodated in the die. The heat losses in vacuum from both sides of the blank will be very small at temperatures below about 600 °C. At higher temperatures additional insulation and highly reflective surfaces of die and cover plate may become necessary. For thin blanks of large diameter, a temperature difference of some 50 to 100 °C between centre and circumference will be difficult to avoid at about 800 °C. Under the conditions selected for the present experiments, smaller temperature gradients are expected.

The cover plate (aluminum or steel) will be held in position at the desired stand off by means of a pneumatic gripping mechanism (not shown) which also provides for the necessary sealing. Immediately before firing (the charge) the cover plate is brought into intimate contact with the blank or the insulating material on top of it through release of the gripping mechanism. The timing of the operations is such that no appreciable cooling of the blank takes place before the forming is complete. After this stage the cooling depends on whether or not the coverplate fractures. If a ductile material like Al is used, no fracturing should occur even in very deep draws.

When rapid and uniform cooling is desired immedialely after forming, several alternative techniques seem to hold promise. They are all based on the assumption that the vacuum space between the cover plate and the blank will provide for a very rapid complete filling by water or other cooling medium. The technical details will be given in later reports when experimental evidence is available.

The blank together with the fastened holding rings are preheated in

a furnace and rapidly transfered to the die. The cover flange with plate in position is then mounted on the die and evacuation of the internal cavities is started immediately. The delay time during which the blank is exposed to cold atmosphere can be made so short (about 10 sec.) that the heat reservoir in the holding ring together with moderate overheating will compensate for the heat losses. Since only moderate clamping of the cover flange is required, a rapid transfer to the watertank is possible. The mounting of the explosive charge is the last operation before the die is lowered to the bottom of the tank. The firing mechanism is triggered by the contact between blank and coverplate when the latter is released.

The forming technique outlined above will have to be studied in preliminary experiments in order to clarify the following points.

1. Magnitude of heat losses and temperature distribution in blank as a function of geometry, insulation and temperature level.
2. Uniformity and rate of cooling after forming.
3. Transmission of dynamic energy from water to blank through coverplate, insulation materials and possible steam at the blank surface.
4. Dimensioning of holding rings,coverplate and other critical parts.
5. Instrumentation with thermocouples, microswitches and pressure gauges.

It is hoped that this technique will give an unusual freedom of choice with respects to the four parameters: working temperature, cooling rate, strain rate and sequence of operations.

5.3 Dynamic plasticity at elevated temperatures.

The effect of temperature on dynamic plasticity of alloys is a complex function of chemistry and previous mechanical and thermal treatments. It is not possible in the general case to predict the plastic behaviour without a detailed knowledge of strain ageing effects, variation of solubility of alloy constituents with temperature, kinetics

of recovery reactions, changes in deformation mechanisms, phase transformations etc. In view of this multitude of parameters,it is not surprising that very few quantitative plasticity data are available for high temperatures and strain rates. It is interesting in this connection that Chromalloy Corp. (12) report improvement of drawing properties with increasing strain rate at 600°-800 °F for tungsten and molybdenum sheet materials.

It is claimed (13) that values for impact properties as measured by the charpy V-notch test can be taken as a guide to the behaviour of a material in a high-temperature explosive forming operation. If this be the case, quite a representative group of steels and refractory alloys can be expected to benefit from a modest increase of forming temperature. The simultaneous effect of strain rate is difficult to predict, but Cooley's observations for the typical elements W and Mo indicate interesting possibilities. On the other hand the critical impact velocity would be expected to go down,and this may restrict the rate of forming.

Of the steels selected in this investigation (Table I) Vascojet 1000, Type 414 stainless and 4340 alloy steel, all have improved impact properties above room temperature in the as heat treated and tempered conditions. The corresponding elongation at room temperature is usually less than 20 % which qualify them as "difficult to work materials". A significantly improved formability below temperatures at which deterioration of mechanical properties become noticable could be of considerable technological importance.

The choice of the above steels is also dictated by their capability to harden through a mastensitic transformation. This permits testing at a given temperature of the same steel in essentially different structural states, i.e.:

1. The austenitic state prevailing during cooling from austenitizing temperature.
2. Martensitic state after tempering.
3. Ferritic state after annealing.

Due to the instability of the austenite below about 720° to 800 °C, both cooling to the desired temperature and forming must take place within narrow time limits depending upon the alloy and the temperature. It is expected that the experimental set up described in the previous section will make it possible to deform the untransformed austenite at any temperature between the Ms point and about 800 °C. If experimental difficulties become insurmountable forming can be confined to the least critical temperature regions.

The transient nature of the austenite and the high temperature required explains why until recently conventional techniques have not been considered for this type of operation. However, current information about the unusual strengthening effects accomplished through "ausforming" have stimulated research activities in this direction (14).

Hot forming of the annealed alloys is probably the easiest operation from a technological point of view since less critical control of temperature, heating time and rate of cooling is required. Extrapolation of data from conventional hot working processes would not be safe since speed effects can be very appreciable at the high temperatures in question.

Also the austenitic stainless steel, type 301, is selected for high temperature experiments. In the heavily cold rolled condition this alloy has very good trength properties up to about 1000 °F for short times, but the ductility at ambient temperature is very low. For this reason cold forming is subject to severe limitations. However, static elongation may increase from 1 to 20 % when temperature is increased to 1000 °F. This indicates that explosive forming may become possible close to the softening temperature. A few experiments will be carried out in order to check this possibility.

The ductility studies will finally encompass the Ti-6Al-4V alloy and a suitable grade of tungsten. These alloys have already been formed explosively, but there is reason to believe that the present experimental technique will permit a wider variation of temperature and rate of deformation than in previous investigations.

For the sake of simplicity the dynamic plasticity will be studied in free forming with the circumference of the blank clamped rigidly in position. Sheet materials of about 2 mm thickness will be used when possible, no intentional variations being aimed at. When possible, a photogrid will be inscribed on the blank surface and used for evaluation of local elongation. The depth of the cup and the local thinning will also be recorded. All test materials will be studied at minimum two representative temperatures, in each case using about three different sizes of the explosive charge at a constant stand off. Due to the exploratory nature of the investigation,little effort can be spent on detailed studies of optimum forming conditions.

Recording of the time dependent displacement of the blank will be made by means of probes in the die. Only in a few auxilliary experiments will shallow dies with planar contacts on the surface be used for studies of the instantanious flow of the material and control of deformation rate.

5.4 Metallurgical effects of hot working.

In addition to the potentially improved formability at high temperatures, a number of interesting metallurgical effects are expected. Since a detailed discussion of the subject would be very extensive only a brief summary will be given in the following.

5.4.1 Effect on fatigue life and stress corrosion properties. As pointed out in section 4.5, both of these properties have been reported to suffer from explosive forming at ambient temperatures. In austenitic stainless steels severe mechanical twinning, martensite precipitation and possibly also microcracks are thought to be main contributors to this effect. Theoretically, one would expect that both twinning and phase transformation can be significantly reduced through working at higher temperatures. The influence on the microcracking tendency is more difficult to predict since little is known about the machanism of formation. However, due to the reduced shock impuls required and changed properties of the material, it would not be unreasonable to

expect a beneficial effect of higher temperatures.

The materials and methods of characterisation selected for the low temperature experiments will also be employed in this case. Strain rates and impact, previously shown to be detrimental at R.T., will be simulated at the high temperature.

5.4.2 Effect on hardening mechanisms. It has been shown recently, that deformation of the unstable austenite followed by martensite transformation before recrystallization can occur, has a significant strengthening effect on steels (15). Thus far, the greatest strengthening has been accomplished in the temperatur range 800° to 1100 °F using alloy steels which transform very slowly in this range. The strength normally increases with the degree of reduction by rolling. At 50 % reduction the yield point is raised about 15 %.

Experiments based on hot rolling at higher temperatures are less conclusive since recovery reactions may significantly influence the result. Between the Ms point and about 900 °F an extreme acceleration of the isothermal transformation has been observed, resulting in an unindentified precipitate in the slip planes of the deformed austenite

The experimental technique selected for the present investigation is expected to increase the speed of operation to an extent which makes possible a more detailed study of the transient states in the two critical temperature regions (above 1100° and below 900 °F). It appears doubtfull that the large deformations indicated to be necessary for maximum hardening will be reached in stretch forming, but compensating effects may still result in a significant strengthening. If successful quenching can be accomplished in the dynamic plasticity studies, representative testing materials will already be available for the three ferritic steels (4340, Vascojet 1000 and 414). Then only a few supplementary experiments will be carried out with the most promising of the alloys. If separate "ausforming" experiments become necessary, the studies may have to be confined to only one of the alloys (4340).

Measurements of hardness and tensile properties supplemented by

metallographic and electron micro-probe investigations will be used to characterize the hardened and tempered alloys.

5.4.3 Deformation mechanisms at high temperatures. It has been claimed (16) that rapid deformation at high temperatures is equivalent to slow deformation at a lower temperature when no metallurgical changes interfere. This hypothesis seem to be supported by the similarity of microstructure in specimens deformed slowly at sub zero, and explosively at ambient temperature respectively. For temperatures in the range of rapid recovery and recrystallization, no pertinent experimental evidence has been located. In our opinion, however, there is reason to expect peculiarities of the defect structure which are characteristic for explosive forming at elevated temperatures. The great importance of the defect structure for phase transformations, precipitation reactions, mechanical properties and annealing behaviour etc. therefore justify a "scanning" of the field. In order to limit the number of experiments, no attempts will be made to study the separate effects of deformation and shock waves.

Since a phase transformation would disturbe the defect structure, only the austenitic stainless steel type 304, in the annealed condition can be used. Most of the test specimens needed will be taken from cups prepared for fatigue and stress corrosion studies (section 5.4.1). In addition, a cup will be formed at the highest possible temperature.

The testing program specified in the previous section will in this case be supplemented by x-ray techniques for the purpose of studying orientation differences in the sub-structure and stacking faults etc. The results obtained at the different temperatures will be compared and analyzed. The annealing properties will then finally be studied in a few auxilliary experiments.

5.5 Technological aspects of hot forming.

The thermal treatment common for the alloys selected for high temperature experiments, are given in Table II.

Conventional forming of these materials at R.T. ~~temperature~~ suffer from the following draw backs due to the high heat treating temperatures involved.

1. A holding jig is usually required for hardening.
2. Process anneals are time consuming because of the controlled cooling rates required in the upper temperature region.
3. Prevention of detrimental scaling is sometimes difficult.

This indicates that there is a potential scope for savings both with respect ~~of~~ to labour and processing time if explosive forming can be accomplished at temperatures, and within time limit which preclude isothermal transformation. Deeper draws, hardening in the forming die and improved material properties are attractive aspects for this process. Similar ideas represent the basis for a "Deep drawn ausforming development program" (14) in which speeding up of operations on a hot-working press is attempted. Only slowly transforming steels can be considered in the latter case.

Although no attempts will be made to scale up the process to more than a blank diameter of about 30 cm, we believe that the experiments will provide a sound basis for an estimate of the possibilities. At the present, forming of blanks up to about 1 m in diameter seem to be within the capabilities of the process. At this diameter the thickness of the cover plate becomes appreciable and it is difficult to predict the uniformity- and rate of cooling. In forming operations without simultaneous hardening (annealed and heat-treated materials), the cooling conditions are less critical.

After free forming at room temperature, maximum thinning usually occurs at the apex of the cup, which also tends to deviate from the spherical symetri. In a high temperature process the central region of the blank will be at a lower temperature than the circumference. It is possible that the resulting strength distribution may significantly influence both the pattern of thinning and the final shape of the cup. Since the temperature gradient can be varied within certain

limits, better free forming results may thus be accomplished.

Finally, reference is made to the potential reduction of spring back.

The experiments in the current investigation are expected to contribute to a better understanding of these technological aspects.

6.0 EXPLOSIVE WELDING.

The use of explosives in welding of metals has been studied rather extensively during the last few years. Although no commercial applications are known at the present time, results recently reported by Holtzmann and Rudershausen (17) indicate that cladding operations may have a bright future.

In conventional processes, cladding is accomplished through hot rolling of two or more metal plates in contact. Usually, careful cleaning and elaborate protection against surface oxidation is required. However, this method is not suitable for many metal combinations of potential interest to chemical industry where light weight and/or strength combined with chemical resistivity may be very important. Composits of titanium, tantalum and zirconium with aluminum and steel might be able to meet these requirements without a prohibitive price penalty. Unfortunately conventional fabrication of these materials is highly complicated because of their disposition to oxygen attack at high temperatures.

Explosive cladding of titanium and tantalum to inexpensive base metals have recently been reported to look very promising. Information about the experimental details are still very scarce, but the need for further development of the technology and extensive investigations of the weld properties is clearly indicated.

The experimental conditions used in previous investigations are summarized in the following:

1. The plates are in contact over the entire surface (18,19,20).
2. The plates are parallel at a certain stand off (21,22,23).
3. The plates form an angle with each other (17,22,24).

All of these conditions have been studied both in air and in vacuum. The results reported are not consistent and no special preferance has emerged. The same applies to the effect of surface preparation which in some reports is claimed to be less important than in conventional techniques. However, the various investigations seem to agree that the

velocity of the collision front should be close to, but not exceed the speed of sound in the given materials.

The physical state of the weld zone is very sensitive to welding conditions. It has been claimed that the characteristic "surface jetting" is essential for a good quality of the weld. This has been disputed by some investigators who claim that a plane interface can be equaly satisfactory and even, that surface jetting may be detrimental to fatigue life due to stress concentration at the ripples. No systematic studies of this problem seem to have been conducted. The chemical nature of the weld is closely related to its mechanical properties. Metallographic investigations have shown that considerable "mixing" of the two metals may take place, sometimes resulting in precipitation of brittle intermetallic compounds. It is not clearly understood whether the weld zone is essentially due to local melting, diffusion or viscous flow. Pearson (24) has presented convincing evidence of melting in a weld with pronounced surface jetting, but this has never been observed in plane welds. Rather, the theory that unusual rates of diffusion occurs under the influence of intense shock waves, seemsto have more confidence in this case.

In order to gain a better control of the weld properties, a quantitative study of the thickness, chemical and metallurgical nature of the weld as influenced by the different process variables would seem profitable. Such data related to the mechanical properties of the composit would facilitate the development of this new cladding technique.

For the present investigation, combinations of tantalum, titanium, aluminum, magnesium, stainless steel and mild steel have tentatively been considered. These materials will be used for a study of the importance of physical state, thickness and chemical composition of the weld zone. For this purpose it will be necessary to employ the various welding methods indicated above using different explosive charge- and geometry parameters. The examination of the specimens will comprise:

1. Metallographic investigations.
2. Electron microprobe analysis.
3. Micro hardness measurements.
4. Measurement of fatigue life.
5. X-ray investigations.

An attempt will finally be made to scale up the process for one of the composits.

7.0 EXPLOSIVE COMPACTION OF POWDER.

Successfull compaction of metallic and non-metallic powders has been accomplished during recent years, using explosive actuated presses (25) and contact methods (26,2,27). In a very simple application of the latter, an explosive sheet is wrapped around a can containing the powder and detonated symetrically from one end. The transfer medium and distance between charge and container can be varied, thus facilitating a certain control of shock wave parameters. Usually compaction is conducted under water.

Thus far, contact methods have given higher densities than presses, usually of the order of 93 to 97 % of theoretical density. According to Paprocki et al.(2) this applies both to ductile metals and brittle, intermetallic compounds such as carbides, borides, silicides etc. and oxides. They further claim that very high green strengths can be obtained with little need for additional sintering. These observations clearly indicate that explosive compaction may give an unusual freedom of variation and combination in the case of composit materials (cemented carbides, cermets dispersion hardened alloys etc). Furthermore, compaction of pure intermetallic compounds to very high densities is of considerable importance for many high temperature applications and for electrodes subjected to severe chemical attack. Compaction of refractory metals is also an interesting field.

The diameter of rods compacted by means of the contact method is at the present limited to about 25 mm, but a further increase to about 50-60 mm is considered to be possible. The length of the rod is mainly limited by the facilities available. The successfull operation of this, apparently simple technique, is highly dependent upon a close control of the magnitude and pattern of the shock wave. Failure to accomplish optimum conditions is obviously the reason for many disappointing results reported by some laboratories. Under proper control even very complex geometries can be fabricated as demonstrated in the Battelle Laboratories (25).

At the present time no detailed information seemsto be available

relating the properties of the compact to the experimental variables. It is the purpose of this investigation to perform a limited variation of the following parameters, using the contact method,

1. Hardness of the particles.
2. Particle size and grading.
3. Temperature.
4. Explosive charge and transfer media.

In order to facilitate the study of grain boundary reactions, the powders will on each hardness level consist of a mixture of two different, but related materials. We expect to use metals and non-metals. The variation of the particle size will be kept within the limits given by the commercially available powders. Tentatively Cu, Ni, stainless steel, Haynes stellite No. 31, W, ZrB_2 and $MoSi_2$ have been considered.

Variation of temperature will be attempted, using a simple procedure similar to the standard contact method. Details will be given when experimental evidence is available. It is expected that a limited temperature increase may have a very signifficant effect on the grain boundary reactions since it comes in addition to the already existing temperatures caused by severe local distortion and friction.

The explosive charge will be varied until optimum density without internal spalling is accomplished.

The compacted powders will be subjected to the following investigations:

1. Metallographic studies.
2. Electron microprobe analysis.
3. Tempering in a hot stage microscope.
4. Measurements of density as a function of distance from surface.
5. Evaluation of mechanical properties.

In addition to the technological aspects, special attention will be paid to the bonding mechanisms at the grain boundaries and the dicipation of shock wave energy in the various powders.

8.0 NEW EQUIPMENT AND INSTRUMENTS.

The original list of instruments and equipment planned to be purchased especially for this project, has been changed in order to meet the requirements of the revised research program. The principal items of the new list are given below:

1. Detonation pit with accessories. (Finished)
2. Power-unit for use in connection with a Philips texture goniometer. (Installed)
3. Cambridge electron probe microanalyzer. (Arrives April 1963)
4. Amsler high frequency fatigue testing machine. (Arrives in May 1963)

The items 1, 2, and 4 are fully paid by the project. The microprobe, however, will only be partly paid by the project (about 1/3 of the total).

REFERENCES.

1. Glen Rardin, A.F. Watts and A.L. Tingley,
Final Engineering Report on
"High Energy Rate Metal Forming".
Locheed Aircraft Corp., January 1960.
OTS PB 171896.

2. S.J. Paprocki, C. Simons, R.J. Carlson,
"Explosive Compaction of Powder Materials".
Creative Manufacturing Seminars 1961-62.
ASTME Paper SP62-29.

3. "Stainless Steels Gain Strength".
The Iron Age, May 18, 1961, page 138-140.

4. Loc. sit. ref. 1, page 242.

5. V. Philipchuk,
"Fabrication by Explosives".
Mechanical Engineering, May 1960, page 48-50.

6. Loc. sit. ref. 1, page 2.

7. C. Zener and J.H. Holloman,
Journal of Applied Physics, Vol. 15, 1944, page 22-23.

8. W.W. Wood, et al.,
Interim Technical Engineering Report on
"Sheet Metal Forming Technology".
Chance Vought Corporation, January 31, 1961.
ASTIA AD 273 179.

9. P.C. Johnson, B.A. Stein and R.S. Davis,
Interim Technical Engineering Report on
"Basic Parameters of Metal Behaviour under High Rate Forming".
Arthur D. Little, Inc., November 1961.
ASTIA AD 271 401.

10. Loc. sit. ref. 1, page 78.

11. C.A. Verbraak,
"How can high-rate forming be applied without deterorating metal properties".
Paper presented at the September 1962 meeting of C.I.R P.
at the Hague.

12. R.A. Cooly,
Final Technical Report on
"Explosive Forming of Refractory Metals".
Chromalloy Corp., December 31, 1960.
ASTIA AD 257 517.

13. G. Gentzsch,
"Hochleistungsumformung" (High Energy Forming).
Part I - Literature Survey
Verein Deutscher Ingenieure, August 1962, page 6.
DK 621.97.07-186.7.

14. W.A. Martin,
Interim Technical Engineering Report on
"Deep Drawn Ausforming Program".
Lyon Inc., July 1962.
ASTIA AD 276 421.

15. R.A. Grange and J.B. Mitchell,
"Strengthening Low-Alloy Steels by Deforming Austenite".
Metals Engineering Quarterly, No. 1, Februar 1961.

16. W.W. Wood,
"High-Energy Forming Methods - a critical review".
The Tool Engineer, June 15, 1960, page 93-105.

17. A.H. Holtzman and C.G. Rudershausen,
"Recent Advances in Metal Working with Explosives".
Sheet Metal Industries, June 1962, page 399-410.

18. P.J.M. Boes,
"Some Aspects of Explosive Welding".
Paper presented at the September 1962 meeting of C.I.R.P. at the Hague.

19. J.L. Remmerswaal,
"The Reaceful Use of Explosives".
Sheet Metal Industries, July 1962, page 482-486.

20. V. Philipchuk,
Final Technical Report on
"Explosive Welding".
American Potash & Chemical Corp., August 1961.
ASD 61-124.

21. W.C. Wilson,
"Explosive Bonding Gains Ground Through Simplified Setups".
The Iron Age, May 31, 1962, page 127-129.

22. D. Davenport and G.E. Duvall,
"Explosive Welding".
Creative Manufacturing Seminars 1960-61.
ASTME Paper SP60-161.

23. J.T. Harris,
"Some Applied Studies of Metal Forming by Explosives".
Sheet Metal Industries, June 1962, page 383-390.

24. J. Pearson,
"Explosive Welding".
Creative Manufacturing Seminars 1960-61.
ASTME Paper SP60-159.

25. J. Pearson,
"The Explosive Compaction of Powders".
Creative Manufacturing Seminars 1960-61.
ASTME Paper SP60-158.

26. D.L. Courson, G.A. Noddin and J.A. Reilly,
"Explosive Compaction of Powders".
U.S. Patent No. 3,002,544, February 28, 1962.
Assigned to E.J. DuPont de Nemours & Co.

27. S.W. Porembka and C.C. Simons,
"Compacting Metal Powders with Explosives".
Creative Manufacturing Seminars 1960-61.
ASTME Paper SP60-102.

TABLE I TESTING MATERIALS

Testing Materials	C	Mn	P	S	Si	Ni	Cr	Mo	V	W	Type of Alloy
Vascojet 1000	0.50	0.30			0.90		5.0	7.30	0.5		Tool steel
SAF No 4340	0.38-0.43	0.6-0.8	0.04	0.04	0.2-0.35	1.65-2.0	0.7-0.9	0.2-0.3			Alloy steel
" 414	0.15 max	1.0 max			1.0 max	1.25-2.50	11.5-13.5			1.0	Martensitic
" 301	0.15 max	2.0			1.0	6-8	16-18				
" 316	0.08 max	2.0			1.0	10-14	16-18	2.0-3.0			Austenitic Stainless
" 347	0.08	2.0			1.0	9-13	17-19		+10xC	Nb-Ta)	Steels
" 304	0.08	2.0			1.0	8-12	18-20				Refractory Metals
AM 355	0.13 max	0.85			0.33	4.25	15.5	2.75		0.1N	Semi-austen. precipit.hard
Ti-6Al-4V											
Commercial grade W											

TABLE II THERMAL TREATMENTS OF HARDENABLE ALLOYS

Alloy	Solution treatm. °C	Hardening	Tempering °C	Annealing °C	
Vascojet 1000	980-1040): 1/2hr.	Air cool	510-65)): 1/2 hr.	816-843): 1 hr.	controlled cooling
4340 alloy steel	843	oil quench	400-632	871	controlled cooling
414 stainless "	982-1010	air or oil cool	200-750	840-870	" "
Ti-6Al-4V	843-954): 1/2 hr.	water quench	482-533):4-24 hr.	732): 1 hr	" "

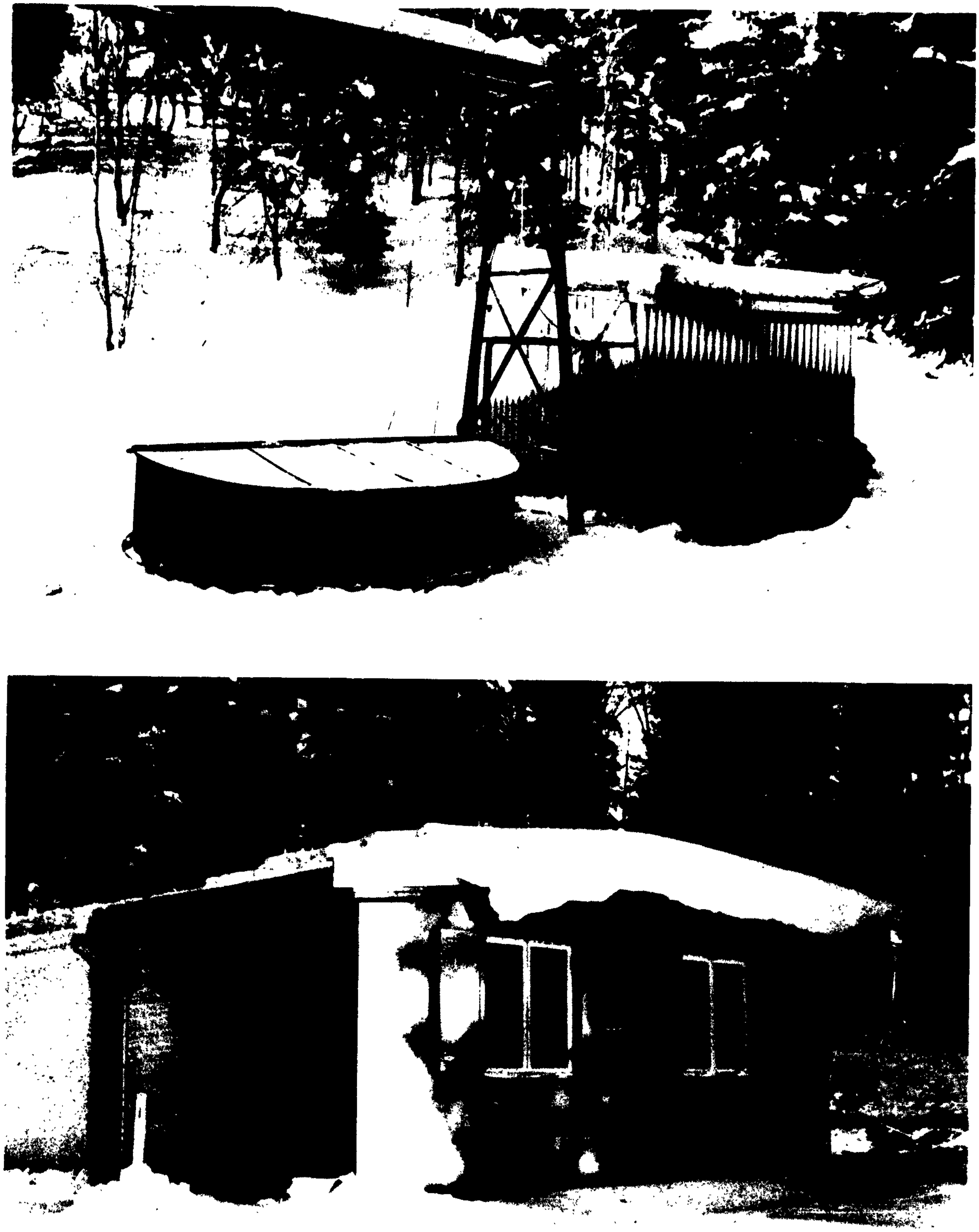
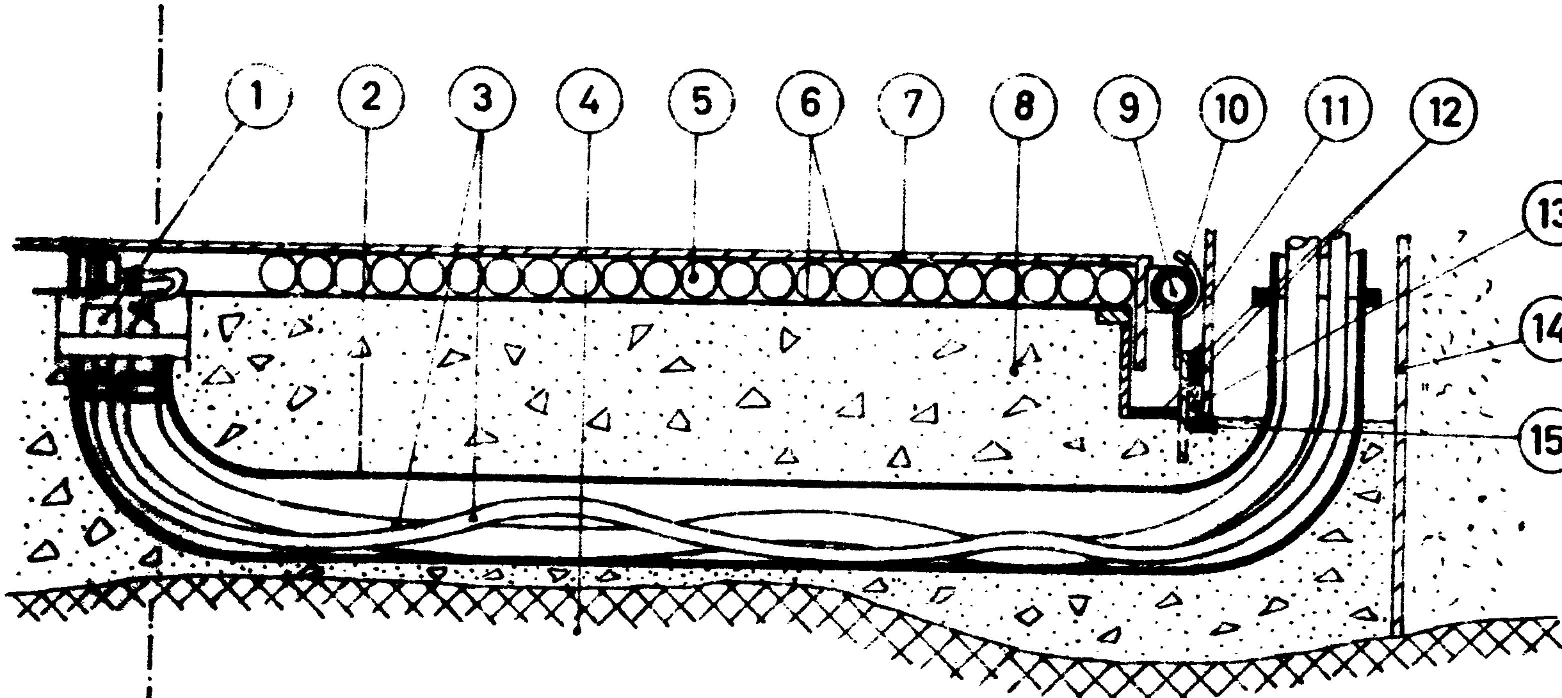


Figure 1 Experimental facilities at Dumpa proving ground of the Norwegian Defence Research Establishment. The detonation pit and preparation shelter are shown at the top and the instrument laboratory below.



1. Back pressure valve
2. Access duct
3. Air supply hoses
4. Solid rock
5. Buffer coil
6. Linoleum
7. Movable steel bottom
8. Concrete anvil
9. Aerator manifold
10. Tube support
11. Steel cylinder
12. None curing sealing compound
13. Rock wool
14. Steel sheet piling
15. Supporting flange

Figure: 2. BOTTOM CONSTRUCTION OF THE DETONATION PIT

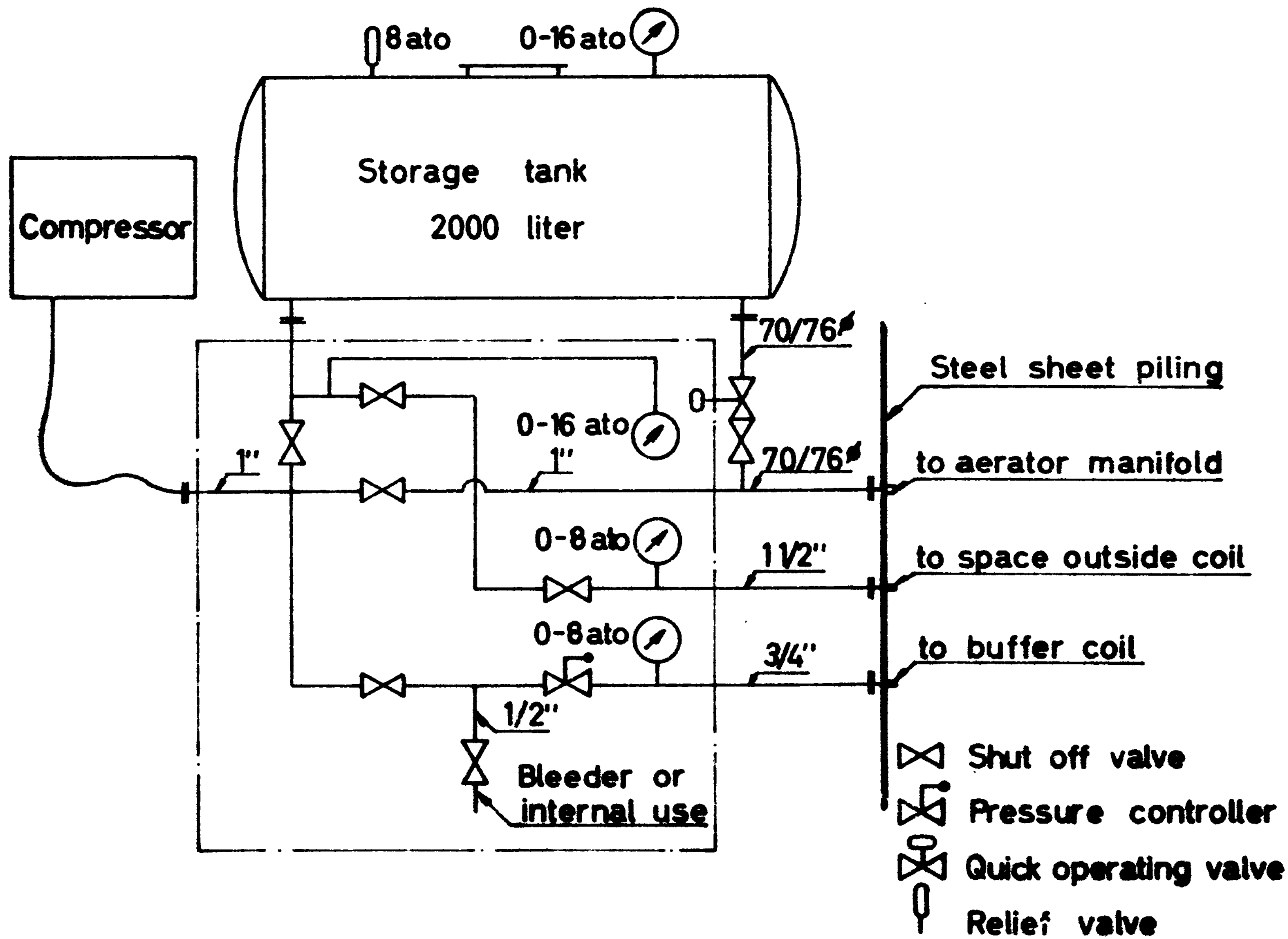
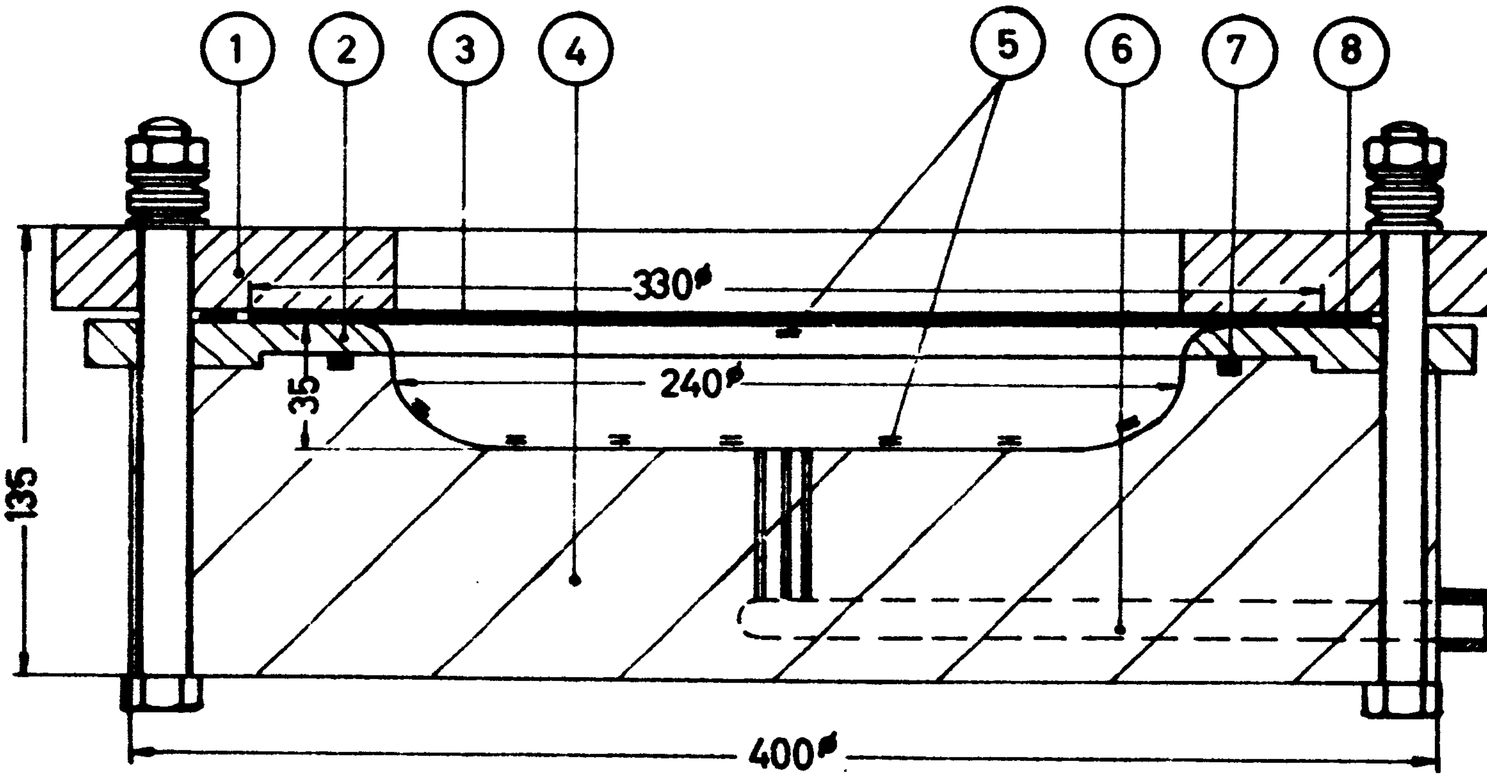
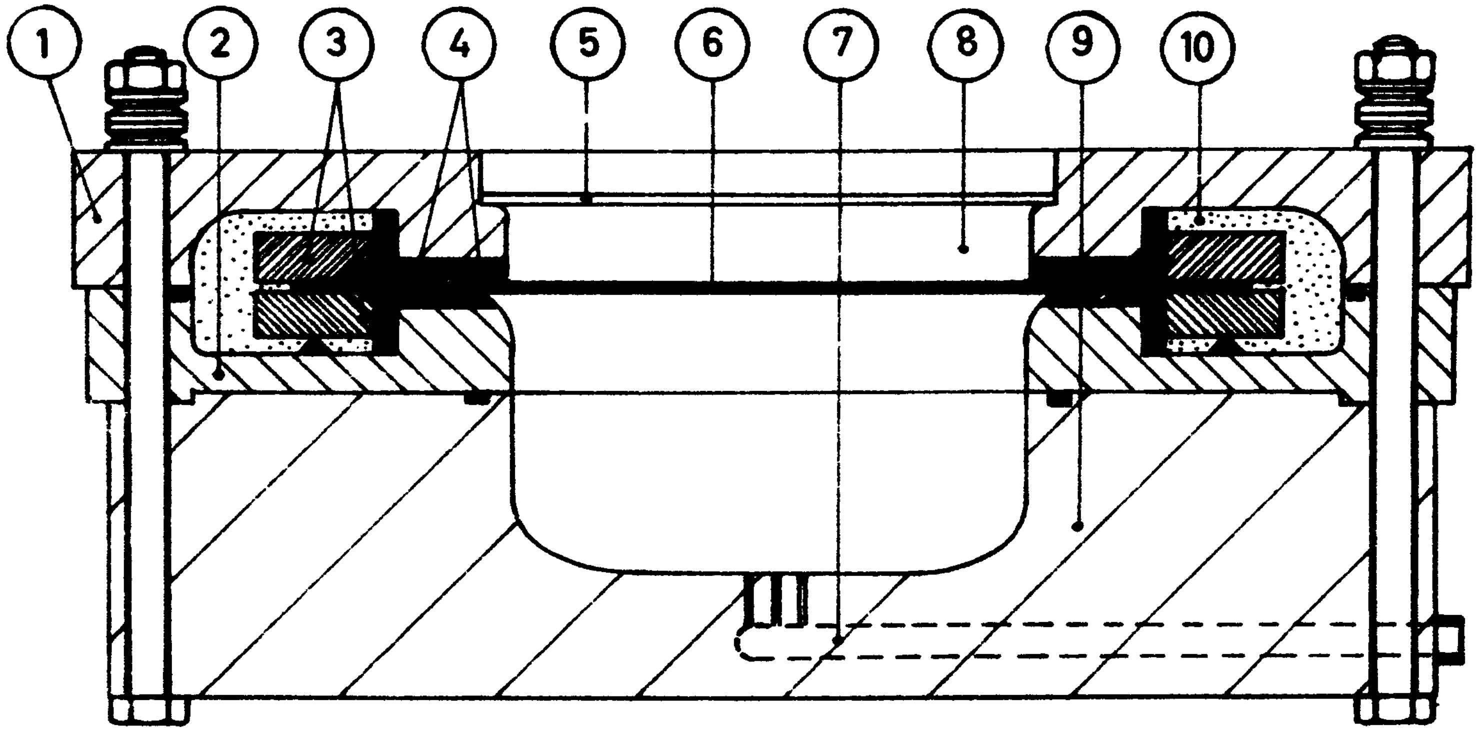


Figure: 3. COMPRESSED AIR SUPPLY ARRANGEMENT



1. Cover flange
2. Draw ring
3. Work piece
4. Die
5. Planar contacts
6. Vacuum line
7. O-ring seal
8. Q-wax seal

Fiaure: 4. MILD STEEL COLD FORMING DIE



1. Cover flange
2. Draw ring
3. Blank holder assembly
4. High strength insulating matr.
5. Cover plate
6. Work piece
7. Vacuum line
8. Vacuum or non-rigid insulation
9. Die
10. Insulation

Figure: 5. MILD STEEL HOT FORMING DIE